CASE FILE COPY

N71-32348

NASA TECHNICAL TRANSLATION NASA TT F-13,901

LARGE PLANETS

S. I. Rasool and T. Encrenaz

Translation of: "Les planetes geantes",
La Recherche, Vol. 2, No. 11, April 1971,
pp. 317-325.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 AUGUST 1971

LARGE PLANETS

S. I. Rasool and T. Encrenaz[1]

ABSTRACT. A general review is given of the structure and compn. of Jupiter, Saturn, Uranus, and Neptune. Also included is an outline for the "Grand Tour" missions planned for 1977-79. 8323b

The giant planets are located at the outer reaches of the solar system /317* where they form a separate world. This distance has long hindered astronomers whose means of observation were insufficient.

However, progress of the last ten years both in ground and space technology have enabled us to ascertain many of the characteristics of Jupiter, Saturn, Uranus and Neptune. Astronomers are particularly interested in their atmospheres. They believe that their compositions have remained very similar to that of the primitive nebula from which the solar system is derived.

The Grand Tour exploratory missions planned by NASA for 1977 and 1979 will take advantage of an astral conjunction which occurs once every 179 years. They will acquire in record time and at a reduced price more exact information on the giant planets. Analysis of these data should clarify the structure of the solar system as formed 4.5 billion years ago.

---

*Numbers in the margin indicate pagination in the original foreign text.

[1]Prof. S. I. Rasool, of Pakistani nationality, studied astrophysics at Paris and was later involved in research at CNRS. Since 1961, he has been working at NASA's Goddard Institute of Space Studies. Therese Encrenaz is working on Jupiter's atmosphere at Meudon Observatory.

Between Venus, the Shepherd's Star, known since the earliest times, and Pluto, located at the limits of the solar system and discovered early in this century, there appear at first glance to be no points in common. Their existence, like that of all the planets revolving around the Sun, is based, however, on the same general explanation. The Sun and its planets actually are derived from a primitive nebula rotating around itself and similar in composition probably to those still found in interstellar space. It is generally accepted that gravitational effects caused this nebula to condense into a disk swollen at the center — the future Sun — and this disk broke into rings which in turn gave birth to the planets. In all probability, such a process is also the origin of the formation of other stars, meaning that the majority of them also possess planetary systems.

Studies of the planets have led astronomers to introduce a classification: Mercury, Venus, the Earth, and Mars comprise the "terrestrial planets" or "inner planets", while Jupiter, Saturn, Uranus, and Neptune comprise the group of "giant planets". Finally, Pluto, the most remote of the planets currently known, falls in neither of the two groups.

What reasons lie at the origin of this distinction between "terrestrial" and "giant" planets? The first is historic in nature. Located at the outer reaches of the solar system, the giant planets actually form a world apart, which was largely unknown for a long time. The distances between the giant planets and the Sun vary between five and forty times the Sun-Earth distance. Jupiter, the nearest, is the largest of these planets, and it continues to intrigue observers by the striped appearance of its disk and the presence of its famous red spot. Saturn, the second giant planet, is particularly fascinating because of its system of rings. The discovery of Uranus by Herschel in 1781 using his 16 cm aperture, 2 m focal length telescope, represented experimental progress, while the discovery of Neptune (and that of Pluto a century later) was a victory of celestial mechanics: In fact, the existence, mass, and orbit of Neptune predicted by the calculations of Adams in England and Le Verrier in France were immediately confirmed by Galle in 1846.

It is not only their positions which lead us to gather these planets in the same family; the second similarity is in their physical characteristics. Their diameters, in the first place, vary between four and eleven Earth diameters — hence, the name. The densities are relatively low — four to seven times less than that of the Earth. In spite of their great dimensions, all the giant planets rotate rapidly around themselves; they also have a great number of satellites (Jupiter is the extreme case with twelve satellites). Finally, the giant planets have a very dense atmosphere composed essentially of hydrogen and helium; pressure may reach several hundred atmospheres.

These principal characteristics of the giant planets can be explained if we refer to their origin and their evolution. The primitive nebulae from which they are derived must have been composed of approximately 90% hydrogen and 10% helium. Nitrogen, carbon, and oxygen occur in only slight quantities (0.1%) and heavier atoms like silicium, magnesium, iron, and nickel, which now primarily comprise our Earth, were present only in very minimal amounts (0.01%). From these elements, a certain number of molecules could be formed in the planetary atmospheres. They were primarily molecular hydrogen, methane, ammoniac, water and molecular nitrogen. But in the course of their history, the composition of the atmosphere of each of the planets could vary, the more volatile elements escaping from the force of attraction of the planet. Thus, taking into account the mass, radius, and temperature of the Earth, we can explain that the Earth's atmosphere lost all its hydrogen and helium. In the case of the giant planets, the gravitational field, an increasing function of the radius, is so great that it prohibits the escape of any element, even as light as hydrogen. This is why the composition of the giant planets remained very close to that of the primitive nebula.

Because of the observational difficulties due to the remoteness of the giant planets, they have long been enigmas to astronomers. The progress made in the course of the last ten years, both in ground and space technology, has enabled us to enrich our knowledge of their atmospheres considerably. However, numerous problems still remain unsolved.

Individual Sources of Emission for Jupiter and Saturn?

Every planet receives a certain amount of luminous flux from the Sun, which can be evaluated if we know the distance from the planet to the Sun. Part of the flux is reflected, and another part is absorbed and re-emitted at greater wavelengths. The spectrum of the re-emitted light may be roughly compared to that of a black body. In fact, the planetary spectra observed do not correspond exactly to the curves for black bodies. The molecules present in the planetary atmospheres absorb part of this radiation at special frequencies, and — as one observes finally — they are absorption rays on a continuous background corresponding to an absorption close to that of a black body.

The infrared radiation of a planet can be estimated theoretically if we know the flux received from the Sun (determined by the Sun-planet distance) and the fraction of the flux which is reflected (known from optical observations of the planet). By Stefan's law, it is possible to deduce the "effective" temperature of the planet from the infrared radiation — that is, the temperature a black body, which is assumed to be homogeneous and isothermic, emitting the same radiation, would have. For each planet, we thus arrive at a theoretical determination of the effective temperature.

In the case of the giant planets, the distances separating them from the Sun are, as we have seen, much greater than the distance from the Earth to the Sun. Therefore, these planets receive much less light flux than we do (in the very special case of Jupiter, it is twenty-seven times smaller than the flux received on Earth). The theoretical effective temperatures of Jupiter, Saturn, Uranus and Neptune, calculated by the method indicated above, are 105°K, 78°K, 55°K, and 43°K, respectively.

It is also possible to obtain an experimental determination of the effective temperatures of the planets by measuring their total infrared flux

from the near infrared millimeter waves. Such an observation is difficult. In fact, the Earth's atmospheric absorption prevents our detecting radiation at these wavelengths. However, in 1969, Low, Aumann and Gillespie of the University of Tucson (Arizona) succeeded in measuring Jupiter and Saturn's infrared flux by means of an experiment performed in an aircraft, and derived a new experimental determination of the effective temperature of these two /320
planets. The results were surprising: 130 to 140°K for Jupiter, 100 to 110°K for Saturn, corresponding in both cases two a flux twice as high as the value predicted by theory.

How is this finding to be interpreted? If it is true that Jupiter and Saturn radiate twice as much energy as the Sun sends to them, this means there is another source of energy involved in these planets' emission. What might this other source be? Is this a problem peculiar to Jupiter and Saturn, or is it a characteristic of all the giant planets? And, finally, what is the meaning of this discovery for the history of the solar system?

For the moment, the existence of an internal energy source in Jupiter and Saturn is deduced only from a single, difficult experiment which needs confirmation. Nevertheless, we may propose several hypotheses on its nature. First of all, we may mention the mechanisms which generally appear in the interior of stars: thermonuclear reactions and radioactivity. The first process can be eliminated, since the occurrence of thermonuclear reactions requires a temperature on the order of twenty million degrees, which is far from being achieved inside the giant planets. Moreover, if this energy source were radioactive in nature, it would originate in heavy elements, such as uranium or thorium, which are present in the giant planets in quantities comparable to those on Earth. Simple calculations show that this process would produce a luminous flux three hundred times lower than that expected from Low's experiment. This hypothesis, as well, must be discarded.

However, other explanations are possible. The first is to assume a phase change between metallic hydrogen[2] and molecular hydrogen at the high temperatures in the interiors of the giant planets.

This hypothesis, recently proposed in the case of Jupiter by Smoluchovskiy of Princeton University, would have the following consequences: an increase in metallic hydrogen at the expense of solid molecular hydrogen would lead to an increase in energy which would be the origin of the flux observed. Also, helium, unable to combine with the metallic phase of hydrogen, would escape from the inner layers and enrich the atmosphere. An experimental determination of the H_2/He ratio in Jupiter's atmosphere would introduce a new element to this problem, but unfortunately such a determination is difficult. We have seen that the atmospheric composition of the giant planets must be close to that of the primitive nebula, that is, we would expect to find hydrogen, ammoniac, methane and helium. Now, if spectroscopy has effectively enabled us to detect the first three of these gases, helium has absorption bands only in the ultraviolet, in a spectral zone where oxygen on the Earth completely absorbs all exterior radiation. We are thus reduced to indirect methods, such as, for example, determining the average molecular weight, which is a direct function of the H_2/He ratio, or measuring the enlargement of certain methane bands. Most recent experiments give H_2/He a value greater than 1; however, knowing the exact value of this ratio would be of prime interest for studying the history and evolution of the planets.

Let us return to the problem of the internal energy of the giant planets: Another explanation is especially exciting if we study its implications for the origin and history of the solar system. It is that of attributing the excess flux radiated by the giant planets to gravitational energy: this analogy to the stars was proposed in 1952 by Kuiper. In fact, we know that the energy liberated by a star in the course of the contraction phase is enormous. Calculations were made in the case of Jupiter, assuming the planet to be in

---

[2] In the metallic phase, elements of hydrogen H are not arranged in H_2 molecules, but in a well-defined structure called a lattice.

convective equilibrium and to radiate a constant flux throughout its contraction. We find that contemporary contraction (contraction was greater during Jupiter's history) of 1 mm/year gives a degree of magnitude quite satisfactory to explain the flux radiated by Jupiter. A similarity occurs between the evolution of the solar system and that of the system made up of Jupiter and its twelve satellites. Both are the result of a gravitational breakdown followed by a slow contraction of the Sun, on one hand, and Jupiter, on the other. But, in the case of Jupiter, contraction did not lead to a temperature increase sufficient to release thermonuclear reactions in its center making it a star.

If the gravitational hypothesis were true, it would have very important consequences for the structure of any eventual "surface" for the giant planets. In fact, if the radius undergoes a contraction of approximately 1 mm/year, there can be no rigid, stable surface, since it would be the object of "earthquakes" and permanent disruptions. Since, because of the dense atmospheres, the surface of the giant planets is not accessible to observations, we are forced to resort again to suppositions.

Storms on Jupiter

The problem of "thermal balance" is not the only enigma posed by the giant planets. Another problem, peculiar to Jupiter this time, concerns its radioelectric flux.

At radioelectric wavelengths, one expects to receive from the giant planets a luminous flux corresponding, in a rough approximation, to the radiation from a black body whose temperature is the effective temperature of the planet in question. Knowing the opacity of the atmosphere as well as its temperature at each frequency, it is possible to calculate the exact value of the flux, which is termed the thermal component of the radioelectric flux.

In the last fifteen years, observers have noted that Jupiter, in addition to the thermal component, emitted an extremely strong flux in the radioelectric

zone. The planet is the second strongest radio source after the Sun. This nonthermal component of Jupiter's flux is detectable from a wavelength of 3 cm, and then increases quite rapidly to wavelengths up to tens of meters. It can be separated into two parts which have different characteristics: decimeter emission, corresponding to wavelengths on the order of a decimeter, and decameter emission at wavelengths of more than 7 meters.

Extending between 3 and approximately 200 cm, Jupiter's decimeter emission consists of apparently constant flux throughout the interval of the spectrum, which would correspond to a thermal emission of several tens of thousands of degrees. It is highly polarized linearly, and very little circularly. This radiation exhibits variations with time, for which the linearly polarized component is probably responsible. Some have sought to establish a correlation between this phenomenon and the changes in strength of solar wind, or with periods of solar activity, but so far no definitive result has been obtained.

At wavelengths of more than 7.5 meters, Jupiter's decameter emission occurs as violent, sporadic explosions of great intensity. Astronomers distinguish two types of explosions, observed at fixed frequencies: "long explosions, which may last for 0.5 to 5 seconds, and "short" explosions of /321
around a millisecond. Moreover, emission occurs at variable frequencies during periods of activity on the order of tens of seconds, which are named "storms". A study of the variation in decameter emission as a function of latitude has shown the existence on the planet of three particularly strong sources whose relative intensities vary as a function of wavelength. In all of them, we observe that the flux density of the decameter emission decreases as frequency increases. As in the case of decimeter emission, many authors have studied the variations with time of the decameter emission, on a scale of several years. The observations have shown the existence of a twelve-year cycle. This value, quite close to both that of the solar activity cycle and to that of the period of Jupiter's orbital movement, does not allow us to attribute the periodicity of decameter emission to either of the possible causes. Finally, a fundamental characteristic of the emission is its

modulation by the satellite Io, the satellite closest to Jupiter. In 1964 it was discovered that the intensity of the decameter flux was multiplied by a factor of 5 when Io was at 90° from the superior conjunction, that is, when the positions of Io, Jupiter, and the Earth formed a right angle.

A Magnetic Field Around Jupiter

What is the origin of all these phenomena? A number of theories have been constructed and at present, although several points are still debated, we have, on the basis of radioelectric information, results which are no longer questioned.

The first steps in the interpretation of the radioelectric flux emitted by Jupiter began with decimeter emission. Although it was discovered later, the decimeter emission is actually the best understood at the present time. Its special features spurred astronomers to find its origin in synchrotron emission by high energy electrons in a bipolar magnetic field. This theory allowed us to explain, in addition to the phenomena cited already, the fact that emission seems to come not from the planet itself, but from an outer layer located at approximately two Jupiter radii from the center of Jupiter. It likewise became possible to explain the variations in decimeter emission with Jupiter's latitude and to deduce the form of the magnetic dipole, the axis being slightly inclined with respect to the planet's axis of rotation. Thus, we became convinced that Jupiter, like the Earth and the Sun, had a magnetic field. As in the case of the Earth, Jupiter's magnetosphere does not extend to infinity, but is contained in a cavity similar to the Earth's Van Allen belts. These belts are made up of two rings of radiation composed of elementary particles (protons and electrons) at high energy.

In the light of this discovery, is it possible to interpret the explosions of decameter emission? The fact that the decameter flux is polarized, circularly or elliptically, suggests a magnetic wave propagation effect in an ionized medium, this medium being Jupiter's ionosphere, and thus supports the

hypothesis of a magnetic field for Jupiter. As to the sporadic explosions of decameter emission, they might be due to occasional jumps of particles from the Van Allen belts into Jupiter's ionosphere, while the circular movement of the particles in these belts may be, as we have seen, the origin of the decimeter flux. In view of this, the influence of the satellite Io is understandable, since its orbit places it inside the magnetosphere. To find exactly what its effects on the decameter explosions are, we must calculate the interaction between a plasma, the particles of which move very rapidly, and a body of unknown conductivity, which is a very complex problem.

Thus, the existence of Jupiter's magnetic field is no longer questioned. From radioelectric measurements, astronomers have succeeded in determining the density of particles in the magnetosphere, and thus the strength of the magnetic field. The latter must be from 10 to 50 gauss at the surface of the planet, or twenty to one hundred times that of the magnetic field at the Earth's surface. Aside from radioelectrical measurements, what more can experiments tell us about Jupiter's magnetosphere? The best solution would be to measure in situ the density of particles in the Van Allen belts of Jupiter and to make direct measurements of the force of the magnetic field in the neighborhood of the planet. Such a program has been planned for NASA's projected flight around Jupiter in a spacecraft around 1975-1980. /322

Another question may be raised concerning Jupiter's magnetosphere, one which brings us back once more to that of the genesis of the solar system: why, of all the planets, do only Jupiter and the Earth have magnetic fields?

As we have just seen, the giant planets still pose enigmas for astrophysicists. But they are not the only ones interested in the solar system. The study of the planets likewise concerns the biologists, since the planets are environments in which life might arise and develop.

Can Life Exist on the Giant Planets?

At present we know that, aside from the Earth, there is little probability that life exists on the terrestrial planets: Mercury and the Moon are practically devoid of atmospheres; the desert-like surface of Mars appears strewn with craters. As for Venus, long considered a sister-planet to Earth, its extremely dense atmosphere of carbon dioxide gas and the high temperature which reigns there make any form of life impossible.

At first, one is tempted to think that the atmosphere of the giant planets, composed of hydrogen, helium, methane and ammoniac forms a very unpromising environment for the birth and development of life. Actually, this is not the case. The appearance of the first stages of life requires an environment quite different from the Earth's atmosphere as we know it today. Laboratory experiments have shown that the synthesis of organic macromolecules such as amino acids and nucleotides, which are the origin of life, requires a gaseous environment of hydrogen, methane, and ammoniac. Such an atmosphere, as the Earth's must have been during the first stages of life on Earth, now exists on the giant planets.

Thus, while we may exclude any possibility of a form of life on these planets similar to that which we currently know, we may, on the other hand, conceive of the appearance on the giant planets of the very first prebiological developments. However, if the chemical constitution of the atmosphere makes this hypothesis plausible, the energy conditions and the environment must still be compatible with the synthesis of prebiological and biological molecules. In fact, the chemical reactions necessary for the formation of organic macromolecules require a temperature greater than those in the atmospheres of the giant planets. They could take place only in the deeper layers. Moreover, for the formation of macromolecules to progress, the environment must be stable and homogeneous. The deep layers of the atmospheres of the giant planets are probably the scene of convective movements. Particularly, in the case of Jupiter, it is questionable that the condition of

stability would be fulfilled. The dynamics of Jupiter's atmosphere pose a number of problems for theoreticians, as well as for observers who, for decades, have been following the strange movements in the atmospheric layers.

The detection, by spectroscopy, of organic macromolecules would be a definitive argument in favor of the existence of life on the giant planets. In 1965 an ultraviolet spectrum of Jupiter taken at the time of a rocket test by Stecher seemed to show around 2600Å an absorption which could not be due to the known components of Jupiter's atmosphere. On the other hand, it could correspond to adenine, one of the most important chemical bodies in biological systems (nucleic acids, in particular). This observation, were it verified, would be even more significant since in the laboratory, in an environment similar to the atmospheres of the giant planets, it would have been shown that adenine was among the very first organic compounds produced. In addition, the color of the macromolecules thus formed proved to be close to that of the clouds of Jupiter and its red spot, whose composition is still unknown. Unfortunately, the detection of adenine has not been confirmed in spite of several attempts, and the problem remains unresolved.

To try and find out more about this question, we must wait on other high-resolution spectroscopic measurements of Jupiter and the other giant planets between 1800 and 3000 Å, an interval in which many molecules can be detected. Such a study might also be attempted in the infrared regions, particularly in the 4-5 μ region where the atmosphere of the giant planets is very transparent and where the atmosphere can be probed most deeply. Because of the opacity of the Earth's atmosphere, these two series of experiments will have to rely on space technology, and recent progress in this technology leads us to hope for improved detection of organic molecules. Finally, in the still longer run, we may look forward to a great deal from a space flight which would explore the planetary atmospheres on the spot.

Future Missions to the Giant Planets

To answer these fundamental questions on the structure of the giant planets, NASA plans two separate missions in the next ten years to the outer regions of the solar system. The first mission sends two Pioneer type space vehicles on a highly eccentric orbit around the Sun, with an apogee at 5.2 times the Earth-Sun distance. This orbit would lead the space vehicle to the vicinity of Jupiter and would for the first time allow an *in situ* exploration of the asteroid belts and the surroundings of the giant planet. The first vehicle, Pioneer F, will be launched in about a year (February-March 1972) and will reach the vicinity of Jupiter in early 1974. Another vehicle, Pioneer G, is planned for April, 1973, arriving in 1975. These Pioneer vehicles weigh approximately 250 kilograms, of which 15% approximately is scientific equipment.

According to current plans, the scientific experiments planned for the mission will be of two types. The first category of experiments is aimed at the exploration of the magnetic environment of Jupiter, by measurements of the magnetic field, the plasma, cosmic rays and charged particles. These determinations will be accomplished when the vehicle passes through the radiation belts of Jupiter which cover approximately three (Jupiter) radii. The second category of experiments concerns the planet itself. The upper atmosphere will be explored by measurements of the ultraviolet radiation intensity emitted by Jupiter between 200 and 800 Å. Such measurements will tell us not only the temperature of the upper atmosphere, but also the H_2/He ratio in this region. Moreover, a photopolarimeter will be placed aboard Pioneers F and G to determine the nature and form of the particles which make up Jupiter's clouds. An infrared radiometer is likewise planned to measure the total quantity of energy radiated by the planet in the distant infrared, which, as we stated above, will enable us to clarify the particularly exciting problem of the possible source of internal energy. Finally, the S-band occultation experiment will contribute a complementary study of the

atmospheric and ionospheric properties of Jupiter. The space vehicle's telemtric signals in the S-band (2300 MHz) will be recorded on Earth while the vehicle passes behind Jupiter. Just before and after occultation by the giant planet, the signals will pass through Jupiter's atmosphere, affecting their frequency, phase, and amplitude. From precise measurements of these parameters, we will be able to deduce the vertical structure of the atmosphere and the ionosphere[3]. The combination of this information with that of the radiometer will give an improved value for the H_2/He ratio in Jupiter's atmosphere.

Any mission headed for the outer regions of the solar system will have to pass through the hazardous asteroid belt. Pioneers F and G will carry the first apparatus for direct exploration of this belt: "penetration cells" placed on the sides of the vehicles will measure the population of solid particles in the mass interval of between 10^{-9} and 10^{-13} grams. Another experiment, using four optical telescopes, will detect asteroids and meteorites by the diffusion of solar radiation as far as a lower limit of 10^{-6} grams.

The variety of experiments mentioned above (if they are all successful in 1975) will give us our first glimpse of the region of the solar system located between Mars and Jupiter, and the surroundings of one of the giant planets. While awaiting the results of this first mission, NASA has already undertaken the preparation of a still more ambitious plan for the end of the 1970-1980 decade: two space vehicles, launched in 1977 and 1979 respectively, will make a "Grand Tour" to the five outer planets. The date of this mission was fixed as a function of special conditions appropriate to it. Between 1979 and 1990, the positions of the planets Jupiter, Saturn, Neptune, Uranus and Pluto in their orbits will be such that a single vehicle launched from the Earth will be able to pass around Jupiter, then Saturn, then head for Uranus and Neptune before escaping the attraction of the solar system. Such an

---

[3] Also, on this subject, see the article by S. I. Rasool and C. de Bergh, La Recherche, No. 1.

alignment of the outer planets is very rare, since it occurs only once every 179 years. It is a remarkable coincidence that this opportunity is occurring at the moment when we are acquiring the technical capabilities to take advantage of it.

Normally, to send a space vehicle in a direct mission to Pluto, which is thirty times as far from the Earth as the Earth is from the Sun, the trajectory duration of the vehicle would be approximately forty years. The "Grand Tour" mission, taking advantage of the positions of the five planets in the coming years, will allow us not only to cover all the planets "for the price of one", but also to reduce the time needed to go to Uranus and Neptune by several years. This is possible by using the very strong gravitational field of Jupiter which, like an enormous magnet, attracts the space vehicle. This property can be used to accelerate or slow down the vehicle. For example, if a vehicle approaching Jupiter passes behind the planet, going around it in the direction of the latter's movement, the vehicle will be accelerated to very high speeds. This is due to the fact that Jupiter moves around its orbit at a velocity of approximately 40,000 km/hr. When the vehicle approaches the planet, it will be caught up by Jupiter for a considerable distance, and therefore, the planet will transmit to it a large part of its own velocity. This acceleration "by turning around", carefully prepared for the "Grand Tour" mission, may be used in principle not only for Jupiter, but also for Saturn and Uranus. The great velocity attained by the three effects reduces the time of flight to Pluto from forty to eight years!

Nevertheless, there is a problem with Saturn. The rings of Saturn, which make the planet so fascinating when it is observed through the telescope, are a danger for the vehicle. A mission passing closely around Saturn is out of the question. If the vehicle passes around Saturn at a great distance, we cannot use the planet's gravity for effective acceleration. The necessity of avoiding the rings of Saturn requires the trip to Neptune to last at least thirteen years. Nevertheless, we can mitigate this difficulty by launching two "Grand Tours" of three planets (see document at end of article). The first vehicle goes around Jupiter, avoids Saturn and goes directly to Uranus

and Neptune; the second vehicle, launched two years later, goes around Jupiter and passes under the south pole of Saturn, which places it in a trajectory away from the ecliptic plane, so that it finishes by passing around Pluto.

What experiments are planned on board these first missions to the outer regions of the solar system? Current plans will be subjected to a final selection of experiments in about a year, but NASA has already chosen the scientific investigation categories. First of all, a "picture" team has been organized, which will be responsible for the preparation of very sensitive television cameras to obtain high-resolution exposures of all the planets. Among the important objectives of this team are studies of the clouds, the red spot, the rings of Saturn and the surfaces of the satellites. In parallel, a "radio" team will take charge of the investigation through radio and radar techniques, with special interest in the experiments with reciprocal occultation by the planets. In addition to these two kinds of investigations, scientists from around the world also propose individual experiments for inclusion in the mission. These experiments include radiometers to measure the thermal balance of the planets, high-resolution spectrometers for research on the minor constituents, and possibly the organic molecules in the deeper atmospheric layers. Also included are ultraviolet spectrometers for exploring the upper regions of the atmosphere, and magnetometers for measuring the magnetic properties of the planets.

Regardless of the combination ultimately adopted for the experiments, if the instruments survive the long voyage, an abundance of new information will result, not only on the structure of the giant planets as they are today, but, through deduction, on the structure of the solar system as formed 4.5 billion years ago!

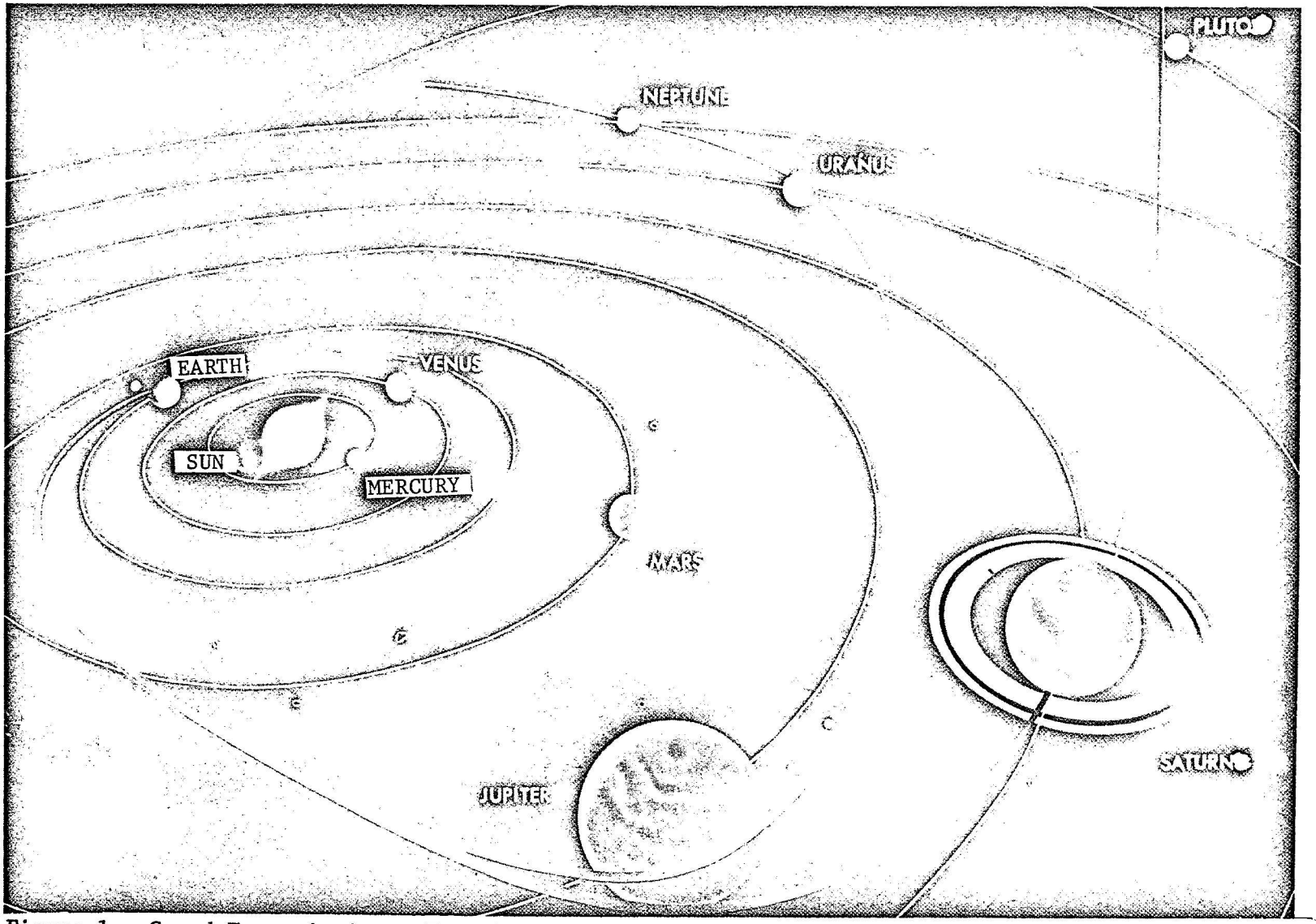
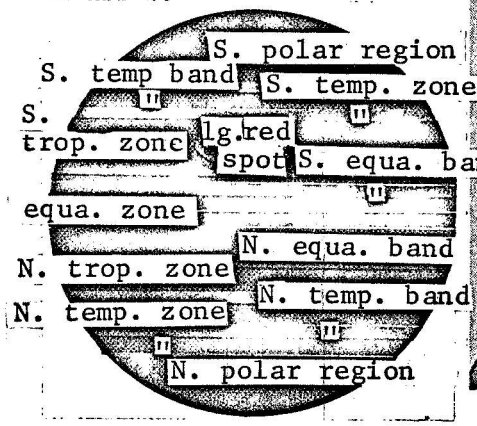
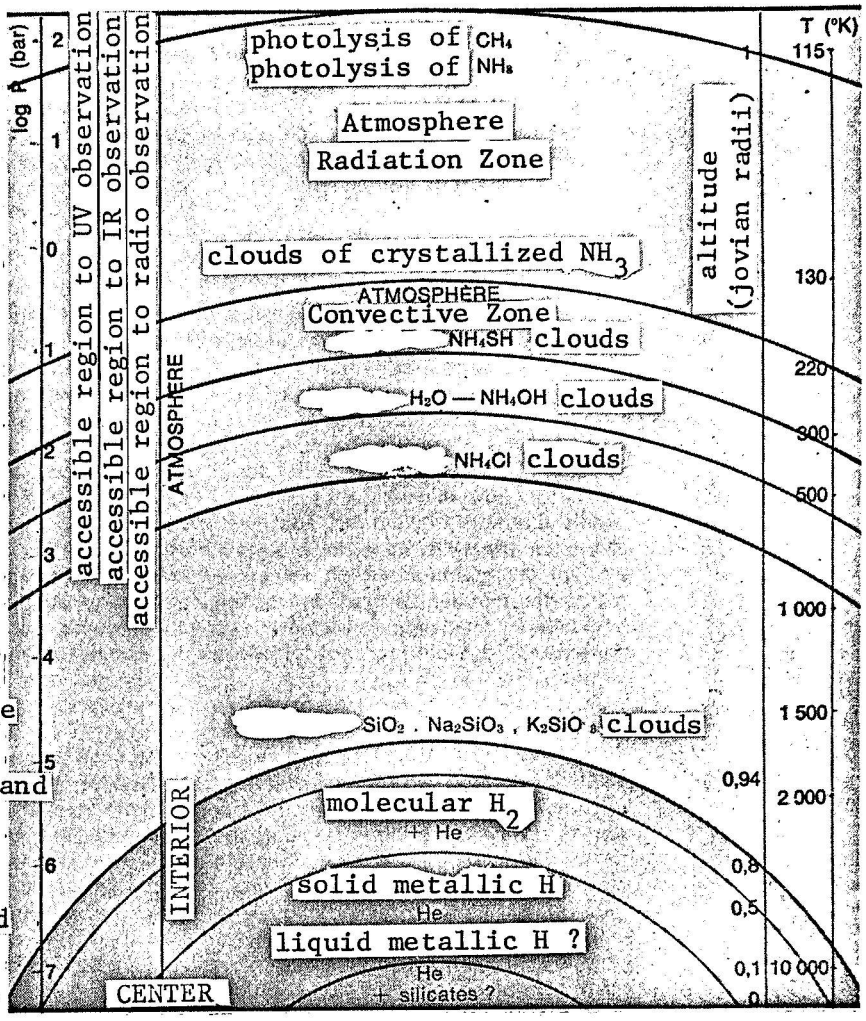


Figure 1. Grand Tour mission. Two missions are planned by NASA for the exploration of the giant planets during 1975-1980. The first of these missions would circle Jupiter, Saturn and Pluto, while the second would head for Jupiter, Uranus and Neptune. Using Jupiter's gravitational field to increase its speed, the spacecraft can reach Pluto in seven or eight years instead of the forty years needed for a direct flight. Neptune could be reached in eight or nine years instead of the eighteen for a direct flight (NASA Document).

(Photo Mount Wilson and Palomar Observatories.)



Jupiter's disk and red spot.



Atmosphere and internal structure of Jupiter.

Among the giant planets, Jupiter occupies a special place. First, because it is the best known planet: as the nearest to the Earth and the largest of the outer planets, it emits a much higher flux than the others, and is thus more accessible to observation. Its distance to the Sun is equal to 5.2 times the distance from the Earth to the Sun; its equatorial radius is

71.400 km, or 11.2 times the Earth's radius. Its mass is $1.88 \cdot 10^{30}$ g, or 318 times that of the Earth, giving an average density of 1.3 g/cm^3 and a high gravitational acceleration, of approximately 2,600 cm/sec^2. The planet's period of rotation about its axis is 9 hrs. 50 min. 30 sec., corresponding to a very high rotation speed. Its sidereal period is 11.86 years. Jupiter has twelve satellites.

The external appearance of Jupiter has long fascinated astronomers, both amateur and professional. The presence of the red spot, the banded structure of the planet, and phenomena of which these are the object are the signs of many unresolved enigmas.

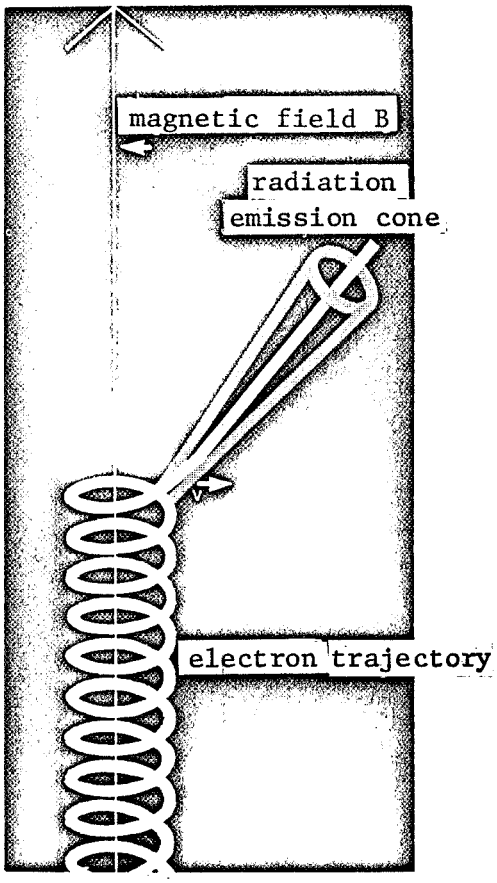
Jupiter's Disk

Jupiter's disk is crossed by "bands" and "zones" whose form, color, and contrast vary with time. There are several systems of notation for the bands and zones. Here we have adopted that of the British amateur astronomer Peek, to whom we are indebted for a great number of systematic observations of the disk of Jupiter. The banded structure is explained by the great rotational velocity. We also acknowledge the existence of very localized currents, circulating parallel to the bands and zones. The red spot dates back probably more than 300 years. Its position, color, and dimensions vary considerably as a function of time. It moves longitudinally as if it were not attached to the planet. Several hypotheses have been put forth on the nature of the spot: one of them stipulates there is a Taylor column, that is, a system of vertical atmospheric currents of considerable height.

The Atmosphere and Inner Structure of Jupiter

Although the interior of Jupiter is inaccessible to observation, it is possible to advance hypotheses on the nature of the deep atmospheric layers and the internal structure of the planet through theoretical studies using the laws of chemical equilibrium and thermodynamic equations. A study of the

composition of the clouds is by Lewis (1969); the representation of the interior is drawn from Smoluchovskiy (1969). The problem of the internal structure, especially the possible existence of a central core, is currently debated. The H_2/He ratio likewise is an unknown. It is not impossible for it to vary from the center to the outside of the planet, and for the atmosphere to be richer in helium than the inner layers. The determination of this ratio is of the greatest interest for understanding the origin and history of Jupiter.



Synchrotron Radiation /321

Under the effect of a magnetic field, electrons describe a helix around the lines of force of the field. During this movement, the electrons emit a pencil of radiation, called synchrotron radiation, contained in a cone whose axis is tangent to the trajectory of the electrons, and whose angular aperture is inversely proportional to the energy of the particles.

Black Body Radiation

A black body is a body which absorbs all the radiation it receives. Planck showed that such a body emits, at a given wavelength, a radiation whose intensity depends only on its temperature. For the Sun, whose temperature is approximately 6,000°K, the maximum radiation is located at around 5 microns. For colder bodies, the maximum shifts toward greater wavelengths. The integral, with respect to wavelength, of the flux emitted by a black body is proportional to the fourth power of the temperature of the body. This is Stefan's law. By analogy, the effective temperature of any given body is defined as being the temperature of the black body which would emit the same integrated flux.

SATURN

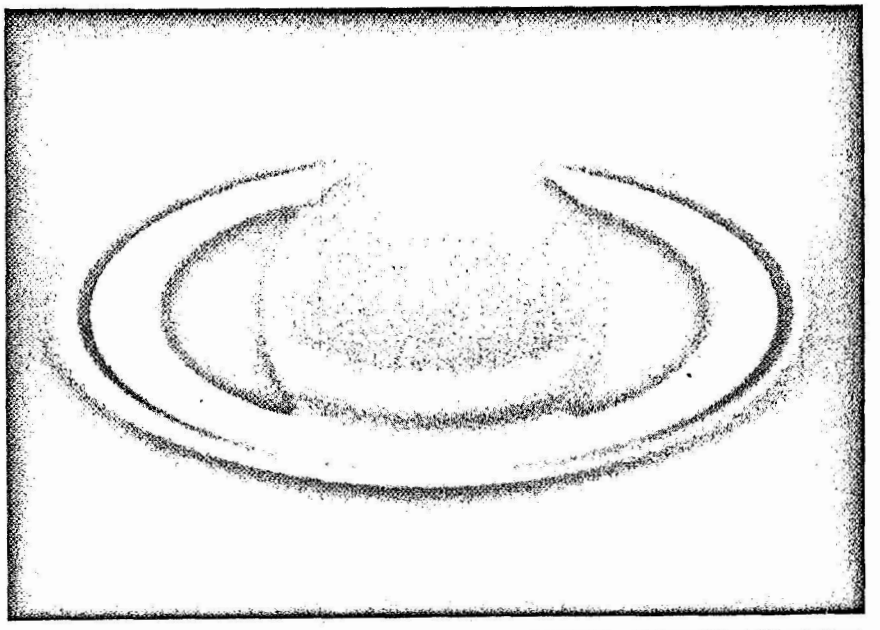
/323

Nine-and-one-half times as far from the Sun as the Earth, the planet Saturn is the second planet of the solar system in size. Its equatorial radius of 60,000 km is 9.5 times that of the Earth; its mass is $5.7 \cdot 10^{29}$ g, which corresponds to an amazingly small average density of -.71 g/cm^3, that is, approximately twice as small as that of Jupiter. Its gravitational acceleration is close to 1,000 cm/sec^2. Saturn's period of rotation is 10 hrs. 14 min. 5 sec., and its sidereal period is 29.5 years. The planet is surrounded by nine satellites.

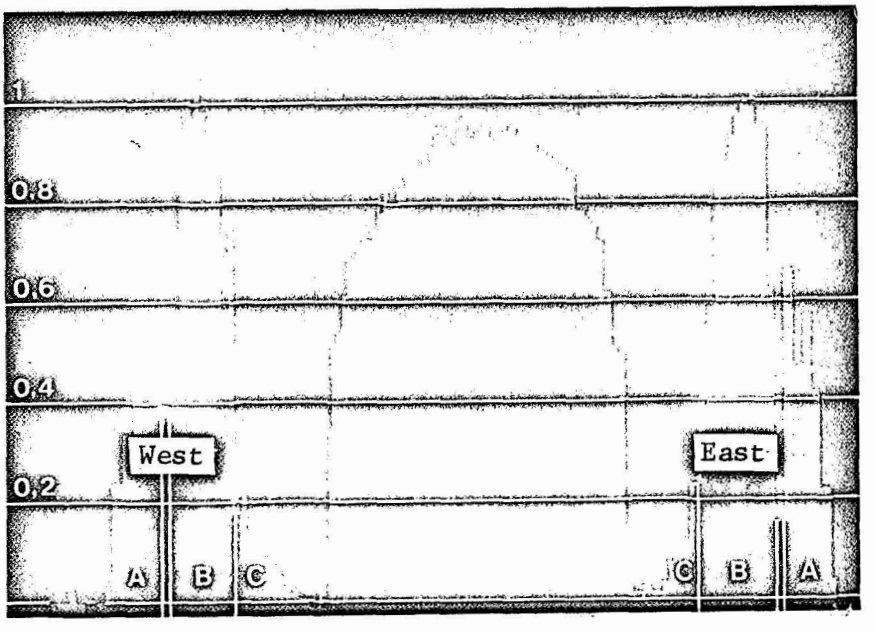
Saturn has many similarities with Jupiter. Its external appearance likewise exhibits bands and zones, much less accentuated than those of Jupiter. Saturn's atmosphere is made up, like that of Jupiter, of H_2, He, CH_4 and NH_3, but because of the low temperature which prevails there, almost all of the ammoniac must be crystallized and part of the methane probably is also. The internal structure is probably similar to that of Jupiter. As to the rings of Saturn, which are one of the strangest objects in the solar system, they continue to interest astronomers and are still the object of controversy.

The Rings of Saturn

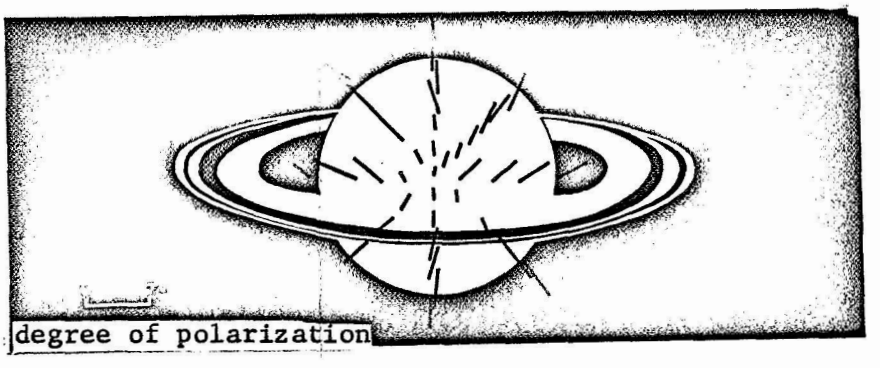
In the rings of Saturn, three principal zones may be distinguished: the outer ring A, the central ring B, which is the brightest, and the inner ring C, which is relatively dark and translucent. They appear to be extremely thin, with a thickness of less than 100 km, and located on the equatorial plane of the planet. Being semitranslucent, the rings of Saturn cannot be solid and must be made up of particles in suspension. Very little is still known about the nature of these particles. On the basis of observations made in the optical and nearby infrared regions, the ice crystal hypothesis has been advanced. Recent exposures taken by Guerin have shown the existence of a fourth ring inside C and very close to it.



Saturn. (Photo: Mount Wilson and Palomar Observatories.)



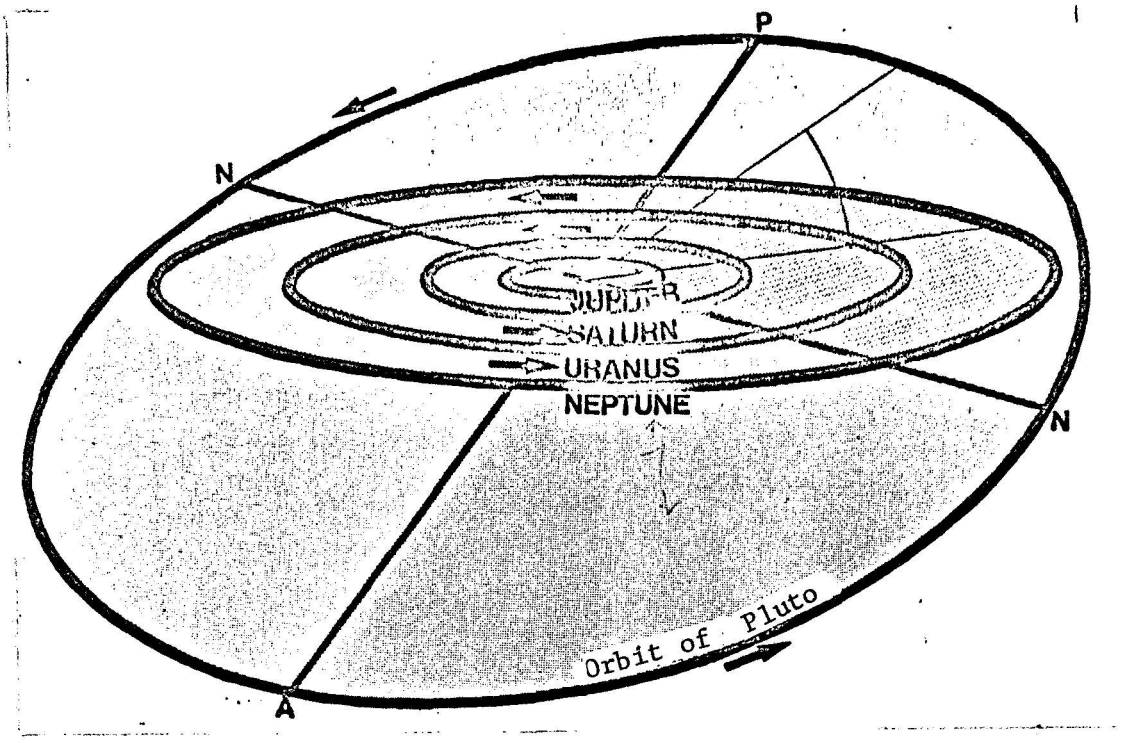
Photometric profile of Saturn's rings obtained by Wlerik with Lallemand electronic camera. (From Planetes et Satellites, Larousse.)



Measurements of Saturn's polarization.

Measurements of Saturn's Polarization

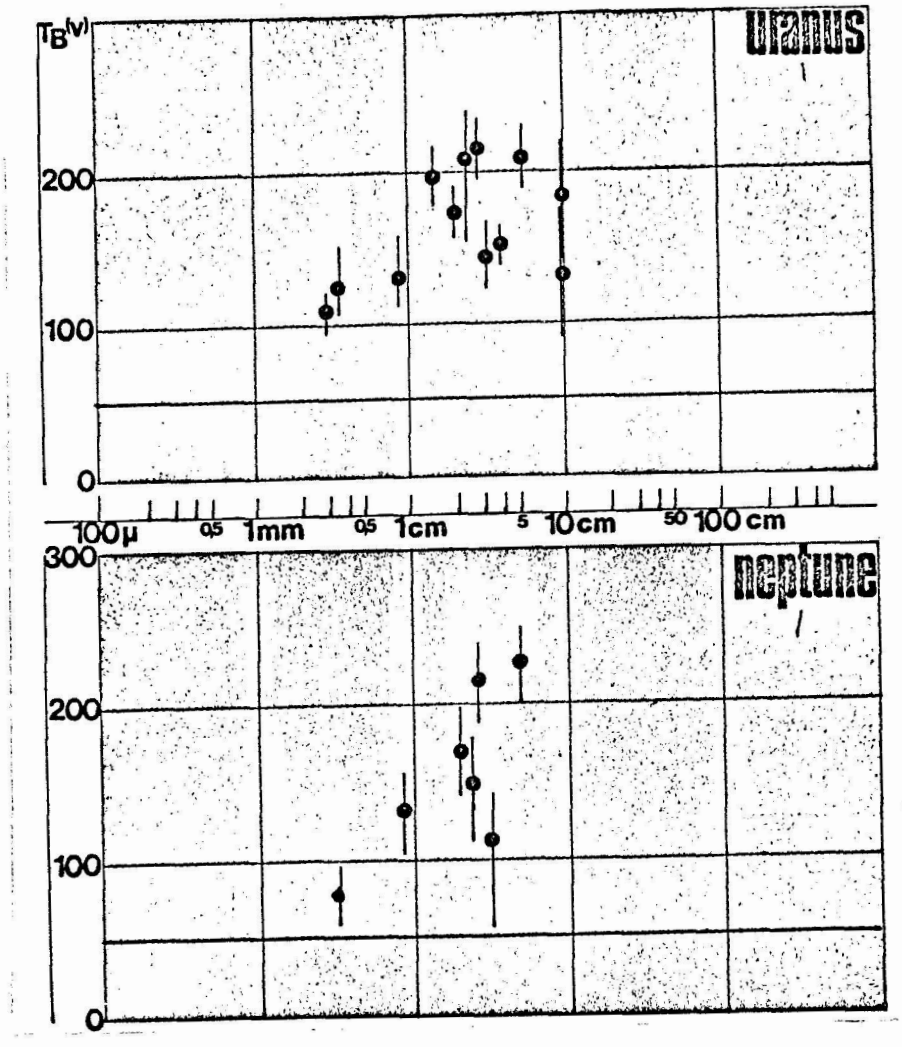
As in the case of Jupiter, observers have studied the polarization of the light emitted by Saturn and its rings in the visible and ultraviolet regions. The figure attached shows the UV results obtained by Hall and Riley in 1968. The high degree of polarization in the vicinity of the poles can be noted. The fact that, in the plane of the rings, the direction of the polarization vectors is not parallel to the equatorial plane is an unexplained problem for the moment. Not much can be derived from polarization measurements of the rings themselves, since their degree of polarization is affected by the light diffused by the disk. Generally, measurements of polarization are very valuable for studying diffusion of light in planetary atmospheres.



Orbit of Pluto.
(From Planetes et Satellites, Larousse.)

With Uranus and Neptune, we enter upon an almost totally unknown world. The distance from the Sun to Uranus is more than twice the distance from the Sun to Saturn, and the distance from the Sun to Neptune is twice as great again. The radii of the two planets have been evaluated respectively as 25,000 km for Uranus, and 24,000 km for Neptune. The period of rotation of Uranus is 10 hrs. 50 min.; that of Neptune is 15 hrs. 8 min. The sidereal periods are 84 years for Uranus, and 248 years for Neptune. The density of Uranus is about 1.3 g/cm^3, with a mass of $8 \cdot 10^{28}$ g, and that of Neptune about 2 g/cm^3, corresponding to a mass of 10^{29} g. Thus, Neptune is the densest of the giant planets.

Uranus has five satellites, with retrograde rotation and almost perpendicular to the ecliptic. From this observation, we have succeeded in showing



Millimeter spectra of Uranus and Neptune.

that the axis of rotation of Uranus was greatly inclined with respect to the plane of the ecliptic and that the direction of rotation was retrograde, which was later confirmed by spectroscopic measurements. Neptune has two satellites. The study of one of them enabled us to determine the inclination of the planet's axis with respect to the ecliptic, which is 29°.

Millimeter Spectra of Uranus and Neptune

The apparent diameters of Uranus and Neptune are too small for one to study the appearance of their disks by optical measurements. The flux radiated

by the planets is too small to make infrared measurement possible. This is why, in the case of Uranus and Neptune, radio observations, especially millimeter and centimeter observations, are of particular interest. At these wavelengths, the flux received by the planets can be attributed entirely to thermal radiation. It is thus possible to construct simple atmospheric models and calculate, from these models, and for each wavelength, the thermal flux one expects to observe. A comparison with experimental results serves as a test for the validity of the theoretical models. The attached figures show the most recent results, presented by Kellerman and Pauliny-Toth, Mayer, and Epstein (1970). The quantity plotted on the ordinate is the brightness temperature, that is, the temperature of the black body emitting the same flux intensity at the frequency considered.

For further information see:

1. Flammarion, Camille. Astronomie populaire (Popular Astronomy), Flammarion, 1955.

2. Smoluchovskiy, R. Infrared Structure and Energy Emission of Jupiter. Nature, Vol. 215, 1967, p. 691.

3. Guerin, P. Planetes et satellites (Planets and Satellites), Larousse, 1967.

4. MacDonald, G. S. F. "What is a Planet?". Atomes, No. 239, January 1967.

5. Cameron, A. W. "The Solar System". Atomes, No. 270, November, 1969.

6. Rasool, S. I. "Planetary Atmospheres", the Origin of life in the Universe, edited by C. Ponnamperuma, Ames Research Center, Moffet Field, Calif., 1971.

7. Sneath, P. Les Planetes et la vie (The Planets and Life). Ed. Groupe Express, 1970.

Translated for National Aeronautics and Space Administration under Contract NASw 2035 by SCITRAN, P. O. Box 5456, Santa Barbara, California 93108.